Life Cycle Analysis of Solar Module Recycling Process

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ABSTRACT

Since June 2003 Deutsche Solar AG is operating a recycling plant for modules with crystalline solar silicon cells. The aim of the process is to recover the silicon wafers so that they can be reprocessed and integrated in modules again. The aims of the Life Cycle Analysis of the mentioned process are (i) the verification if the process is beneficial regarding environmental aspects, (ii) the comparison to other end-of-life scenarios, (iii) the ability to include the end-of-life phase of modules in future LCA of photovoltaic modules. The results show that the recycling process makes good ecological sense, because the environmental burden during the production phase of reusable components is higher than the burden due to the recycling process. Moreover the Energy Pay Back Time of modules with recycled cells was determined.

INTRODUCTION

In recent years a rapid growth of the production capacity and installation of photovoltaic modules has been observed. For the next decades a growth of 15% is predicted [1]. Due to their long lifetime the amount of end-of-life modules is still relatively small. It is estimated to be about 14 MWp in 2006 [2], and this quantity will increase rapidly as the PV market grows. In Europe alone, the emergence of end-of-life modules is estimated to be 290 tons in 2010 and 33,500 tons in 2040.Other concepts for recycling crystalline photovoltaic modules were examined in scientific studies, but none of them was realized in an industrial scale until now. Regarding the growing quantity of end-of-life modules producers of photovoltaic products have to take the responsibility of the final treatment. Due to the curtness of silicon, it is necessary to establish a recycling concept for all kinds of photovoltaic modules that regards environmental aspects and statutory regulations. Competing technologies to high-value processes like the one of Deutsche Solar AG are low-value recycling technologies like the treatment in a recycling plant for laminated glass or disposal on a landfill after treatment in a municipal incineration plant.

RECYCLING PROCESS OF DEUTSCHE SOLAR AG

SolarMaterial, a business unit of Deutsche Solar AG is engaged in various recycling loops along the succession of production steps from silicon as raw material to photovoltaic modules. The presented study deals only with the module recycling process. Regarding a sustainable use of silicon as raw material, the other recycling activities are just as important.

Recycling activities along the production steps from ingot growing to module assembly:

- sides of multi crystalline ingots
- bottom of multi crystalline ingots
- tops of multi crystalline ingots (partly)
- broken wafers
- faulty processed cells
- cell breakage
- production rejects of ingots

A silicon photovoltaic module is composed of silicon solar cells, metal contacts between the cells, encapsulation layer that enclose the cells, front glass plate and a back-side foil or a second glass plate on the back side. Often the module is framed with aluminium and contains a contact box. The module recycling process of Deutsche Solar AG enables the recovery of wafers and the recycling of glass and metals from crystalline solar modules [3]. By burning off the laminate in an furnace the module compound structure is disunited, so that solar cells, glass and metals can be separated manually. Glass and metals are and given to recycling partners, while the unbroken cells are etched in the etching line of SolarMaterial. Broken cells are also collected for reuse as raw material for ingot growing after etching with a different technology. In the etching line the metallization, anti-reflection coating and pn-junction of the cell are removed subsequently. The clean wafer, which is the final product of the recycling process, can be processed again in a standard solar cell production line and integrated into a PV module. During the thermal treatment energy is consumed by the furnace, afterburner and washer. In addition, the washer consumes water and leach. Important outputs are air emissions and different waste streams. During the chemical process different chemicals are required. Moreover, water and energy are consumed in the line and the exhaust gas washer. The chemicals used for etching are treated chemically and physically. The resulting sludge is disposed of. Resulting water is delivered to a sewage treatment plant. The process and important in- and outputs are summarized in Figure 1.
In this study the transportation of the modules to the recycling plant is not considered, because it does not depend on the recycling technology but on the collection system.

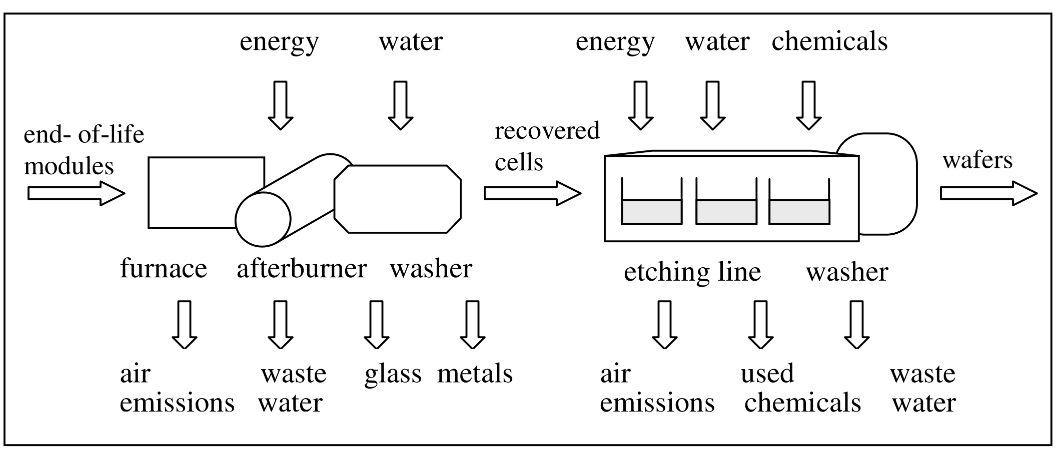

Figure 1. Important in- and outputs during module recycling.

ENERGY CONSUMPTION

An assessment of the total energy demand during the recycling process gives a first insight on the environmental effects of the process. The total energy consumption is composed of the demand of natural gas and electrical energy of the exhaust gas cleaning during the thermal treatment as well as the consumption of electrical energy of the etching line. The amount of primary energy was converted to electrical energy with an assumed efficiency of 35 percent. For the calculation of the energy generation per year a Middle-European location with 1000 kWh/m²/year and a performance ratio of 0.75 is assumed. The results of a comparison of a module with new wafers and a module with recovered wafers of the recycling process of Deutsche Solar is shown in Table I. For wafer production a high energy input is necessary. The recycling of 72 wafers for a new module takes 92 kWh_{el}. Which is 30 % of the energy input for the production of 72 new wafers (306 kWh_{el}).The calculation shows that the Energy Pay-Back Time (EPBT) of a module with recycled wafer is 1.7 years shorter than of a standard module (EPBT of a new module with above mentioned assumptions: 3.3 years).

Table I: Energy consumption and generation during the production and use phase of a module of 160 Wp, 72 multicrystalline cells 12.5 x 12.5 cm (energy consumption during production are based on data of 2004 [4]).

	module with new wafers	module with recycled wafers	Unit
wafer production (multi)	306		kWh_{el}
recycling process		92	kWh_{el}
cell processing	49	49	kWh_{el}
module assembly	45	45	kWh_{el}
Total	400	186	kWh_{el}
energy generation	120	120	kWh_{el}/year
EPBT	3.3	1.6	years

Figure 2. Field photovoltaic installation on the German island Pellworm before disassembling for recycling

The calculation is based on average data of the treatment at the pilot plant in Freiberg. In the next months modules of the oldest field photovoltaic installation in Germany will be treated [5]. This installation was installed 1983 with an efficiency of 8%. After reprocessing and module assembly the recycled installation will have an efficiency of about 14% thanks to improved cell processing.

LCA

In the presented LCA a standard module was investigated with 72 cells (12.5 x 12.5 cm), Tedlar as backside foil and an aluminum frame. For the evaluation of the environmental impacts, the CML Baseline-2000 method of the institute of Environmental Science in Leiden (CML) was used. The analysis was performed with the software Simapro 6.0. Calculations are based on Deutsche Solar data as well as data from the ecoinvent 2000 database [6]. The dataset for production of silicon wafers is based on analysis of the years 1995 to 2000. The presented LCA was done before more recent data were available. The described in- and outflows including the treatment of wastewater and used chemicals are considered. The environmental impact of producing the collected amount of glass and metals as well as of producing the amount of recovered wafers is credited to the impacts of the recycling process itself. In the following the results of the characterization is presented. The process is evaluated regarding seven impact categories, for example “climate change”. For each category a specific indicator (for example kg CO_2-equivalent) is calculated as the weighted sum of individual emissions. In Figure 3 the environmental burden (positive contribution) are opposed to the environmental disburden (negative contribution) of the recycling process. The sum of negative and positive contribution is scaled to 100%, because each category is evaluated by a different indicator with its own unit.

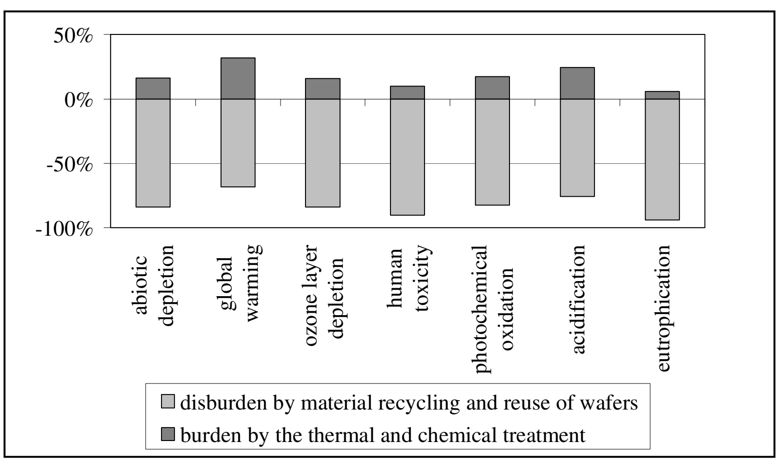

Figure 3. Disburden and burden of the recycling process of Deutsche Solar AG.

Due to the avoidance of new wafers and recycling of glass and metals the absolute impact values are negative for each category. This shows the superiority of high value recycling processes compared to disposal solutions with low environmental impacts but without material recycling or the possibility to reuse individual components. The results also show that the burden of the environment is mainly related to the energy consumption during the thermal treatment and the use of chemicals in the etching line. As a result it is important to decrease the energy consumption during the thermal treatment and to cut down the consumption of chemicals in the etching line. The actual operational mode of the furnace and the etching line posses further room for improvement regarding both aspects [7].

COMPARISION WITH ALTERNATIVE PROCESSES

At the present time there are two alternative disposal scenarios for photovoltaic modules. The simplest possibility is a treatment in a municipal waste incineration and subsequent disposal at a landfill for inert waste. At least in Europe a thermal treatment before the deposit on a landfill is necessary to fulfill the criteria for the acceptance of waste at landfill sites [8]. The advantage of this solution is that it is not necessary to acquire end-of-life modules separately to commercial or industrial waste. The main disadvantage is the loss of raw material like silicon. In the examined scenario it was assumed that the aluminum frame is removed before the thermal pre-treatment because of its high economic value. A municipal incineration plant is a large-scale plant unlike the furnace of DS. Hence the energy consumption of a municipal incineration plant per kilogram is substantially lower.

A comparison of the process of DS and the described scenario is shown in Figure 4. In this figure the recycling of the aluminum frame is not considered, because it is carried out in both scenarios and only a part of photovoltaic modules is framed with aluminum.

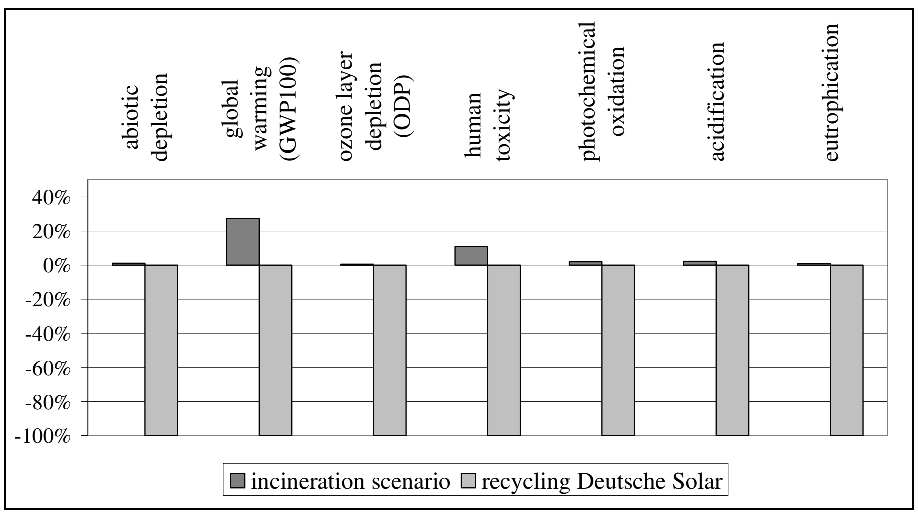

Figure 4. Comparison of an incineration scenario with the recycling process of DS.

Another scenario is a shredder process with subsequent sorting and thermal treatment of one fraction, that is deposited on a landfill. It is expected that the aluminium frame is removed before the shredder process. The recovered glass fraction can be put back into glass production. The second fraction consists of organic material, metals and crushed solar cells. Due to its high organic content the thermal treatment before a deposit on a landfill is necessary in Germany and other countries. The energy consumption of a shredder process is two orders of magnitudes lower than the recycling process. But in the shredder scenario only glass and metals can be recycled. The silicon of wafers is lost in this scenario. The expenditure of energy for the production of silicon wafers and material for ingot growing is relatively high (see table I). This fact justifies the operation of the DS process even with higher energy consumption. In general high grade recycling solutions are preferable to low grade solutions. In consideration of the scarcity of silicon for the PV industry the reuse of wafers is an additional advantage.

SUMMARY

The energy consumption during the recycling process is essential. Nevertheless the use of recycled wafers for wafer production instead of new ones can halve the EPBT of a module. Due to the reuse of recovered wafers and the recycling of glass and metals the recycling process of Deutsche Solar AG leads to a decrease of environmental burden by avoidance of the production of new wafers and material like glass. Other examined disposal scenarios do not represent a high value recycling, because the material with the highest value is lost by deposition on al landfill.

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